IMPACT OF INVERTER CONFIGURATION ON PV SYSTEM RELIABILITY AND ENERGY PRODUCTION

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ABSTRACT

The loss of potential revenues due to PV system failures should be taken into consideration when the system's life cycle cost predictions are calculated. We demonstrate a procedure for quantifying the effects of inverter failures (as most dominant) on total lifetime PV system energy production, and investigate the suitability of several inverter configurations based on criteria of total lifetime energy output and life cycle costs. The overall PV system performance penalty due to inverter failures depends on several factors, such as the reliability characteristics of the inverter, inverter configuration and repair time. Using Monte Carlo analysis, a performance-adjusting coefficient that accounts for these factors is proposed, and a straightforward analysis for determining the optimal inverter configuration is described.

INTRODUCTION

In conventional energy sources, failure-related damages are limited to repair costs. When the generating unit is idle, no fuel is consumed, and production resumes when failure is cleared. In PV systems, the fuel is free and every time the system is non-operational, the possibility for energy production (and revenues) is lost. The loss of potential revenues is important, since the large initial investment for a PV system is usually compensated by the price paid (or avoided to be paid) for electricity during the lifetime of the system. In evaluating the payback time and energy price per kWh generated by such system, the system is usually assumed to work without interruptions. PV systems are highly reliable, but like any complex system, they may fail. Neglecting the effects of those failures may lead to unreasonably optimistic performance and life cycle cost predictions. Studies [1,2] have shown that the majority of PV system failures may be attributed to inverter failures, and in this paper, we demonstrate a procedure for quantifying the effects of inverter failures on total lifetime PV system energy production, and investigate the suitability of several inverter configurations based on criteria of total lifetime energy output and life cycle costs.

We consider the following inverter configurations:

a) Single inverter system
b) System with N identical smaller inverters (N times smaller rated power), each connected to a portion of the system (string) corresponding to its capacity.
c) System with N identical smaller inverters (N times smaller rated power), connected to the entire system and working in parallel.

SYSTEM CONFIGURATIONS

In the case of a single inverter (case **a**), we expect a certain number of failures F during the lifetime of the system. When the inverter is operational, its output is equal to its input reduced by conversion losses, and when it is non-functional, the total output is zero. In the case of multiple string inverter system (case **b**), we expect N times more failures, but each particular failure would just reduce the overall conversion ability of the system, and will not shutdown the entire system since the remaining $(N\text{-}1)$ inverters will continue to operate. Since the expected number of failures is $N \cdot F$, but each failure reduces the system's conversion ability by N times smaller amount, the total expected lifetime energy production is the same in both cases. Multiple-inverter configuration, however, improves the reliability of the system, since each particular failure does not lead to total system failure. Note that throughout the paper we assume that all inverters, regardless of their size, have the same conversion efficiency, failure characteristics and that the repair time is distributed in the same way. The larger the discrepancies in inverter capacities, the larger is the potential for discrepancies in these characteristics, however, the inclusion of these discrepancies may not present difficulties in the numerical approach presented further in the text.

Instead of having a dedicated inverter per section of the PV array, inverters can be connected in parallel (case **c**), effectively sharing the total conversion load. When one inverter fails, depending on the instantaneous total DC power, remaining inverters may process part, or even all the power that was being converted through the failed inverter. The PV inverter has to be able to handle maximum (or close to maximum) expected DC power at its input terminals. Due to the nature of the solar energy conversion process for Silicon-based solar cells, the maximum solar cell DC power output (and inverter input) is expected under circumstances such as a combination of high insolation and relatively low temperature, which is not likely to occur often. Therefore, a PV inverter works most of the time at power levels significantly lower than its rated power. Moreover, the inverter's conversion efficiency depends on its fractional loading, defined as a ratio of the input power to its nominal DC rating, as shown in Fig. 1. The inverter size is chosen so that its cost and inverter-related losses are minimized, i.e. its nominal power should be as small as possible, to provide high conversion efficiency during normal operation, while not too small in order to minimize revenue losses when its input power has to be limited. There is no need for additional circuitry that will protect the inverter when its input power is higher than its rated power. At those times, the maximum power point tracking algorithm simply moves the inverter away from the maximum power point, maintaining the input power at the rated power.

Fig. 1a). shows a typical histogram of the DC power expected at the inverter input terminals over a period of one year. Inverter efficiency curve is superimposed, showing the misalignment between the actual power being processed and inverter efficiency. Using this data, the expected inverter efficiency over a period of one year is calculated, and shown in Fig. 1b). We note that, although inverter efficiency is rated as 95% at full load, for fractional loads lower than 0.5 it may drop well below 90%. Also, inverter efficiency is lower than 80% for more than 25% of the time.

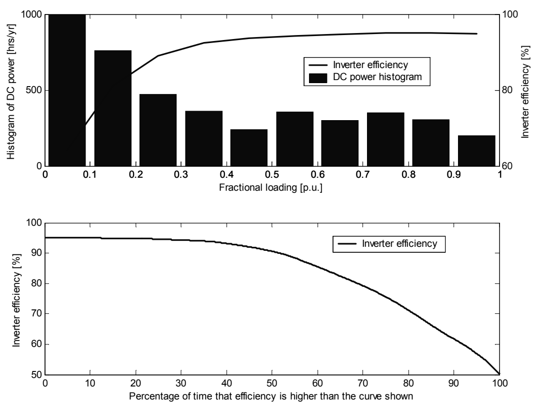

Fig. 1. (a) Typical PV inverter output histogram and its corresponding efficiency, (b) Efficiency duration curve.

The multiple-inverter configuration may therefore be beneficial. In the case of a failure of one inverter, the remaining inverters will continue working and will share the additional load imposed on them. In the case that the input power is higher than the total rated power of remaining *(N-1)* inverters, they will all operate at their rated power. The expected energy loss due to the inverter malfunctions over the lifetime of the system depends on the number N of inverters connected in parallel, and will be a non-increasing function of N.

A simple control strategy might improve overall multiple-inverter system conversion efficiency. As noted previously, PV inverter efficiency depends on its fractional loading, which is a probabilistic quantity. In a multiple-inverter configuration with N inverters connected in parallel, when the total input DC power is lower than the total rated power of *(N-k)* inverters, we might purposely turn-off k inverters, which will force the remaining inverters to operate at higher fractional loadings, and therefore improve their conversion efficiency. This simple control strategy is explained using (1).

$$N_{on} = \min\left(N, ceil\left(\frac{P_{DC}}{P} \right) \right) \qquad (1)$$

where N_{on} is the number of inverters that should be online, N total number of inverters, P_{DC} total instantaneous DC input power, P nominal power of each inverter, and the function *ceil* rounds to the nearest integer towards infinity. Note that this control strategy may need to be adjusted in the case that the peak conversion efficiency occurs at a power level below rated power.

PERFORMANCE ANALYSIS

To quantify the above-mentioned effects, we introduce a coefficient that adjusts the total lifetime PV system energy output taking into account inverter-related failures. The reliability coefficient is defined as a ratio of the expected lifetime energy production of the PV system with N inverters (including PCU failures), and the energy that a single-inverter system would have produced if there were no PCU-related failures. The coefficient depends on the geographical location of the system, number of inverters, their configuration and the underlying random distribution of both failure and repair times.

We treat both time between failures (TBF) and repair time as random variables. Inverter manufacturers typically do not provide failure data, but mean times between failures (MTBF) between 1 and 16 years have been reported based on the field data [1]. These data can be used to model the TBF as an exponentially distributed random variable, with parameter $\lambda=1/MTBF$. Several initiatives aimed at collecting the performance data for a large number of various PV systems are currently taking place, which would likely provide better insight into the appropriate distributions and parameter values to be used for modeling TBF.

The repair time varies greatly, and can be anywhere from couple of hours (for large continuously monitored systems), to a couple of months (for remote installations and large installations that depend on manufacturer's service). Typically for residential non-monitored systems, it includes failure identification period of up to one month (using meter data from the utility bill), followed by one to two weeks for system repair. For large installations (either in size or volume) several monitoring strategies can be utilized, ranging from continuous monitoring of system performance and comparison with predicted output obtained using meteorological data, to a less frequent (weekly, bi-weekly) phone-in of inverter diagnostic data to a central computer. The availability of spare parts or a spare unit – a situation more probable in the case of a system with multiple, standardized inverters may significantly decrease the repair time.

To obtain the statistically valid estimate of the coefficient, we use the Monte Carlo simulation. The 20-year lifetime of PV system operation (including failures) is simulated for a given inverter configuration, using randomly generated data, obtained using chosen distributions for TBF and repair time. The total produced energy is calculated, and the procedure is then repeated, where for each simulation a new set of failure/repair data is randomly generated. The result of such Monte Carlo analysis is the expected energy production of the system including the performance loss due to inverter-related downtimes. The value of reliability coefficient is then simply obtained by dividing the expected energy production by the energy that would have been produced by a single-inverter system if there were no failures.

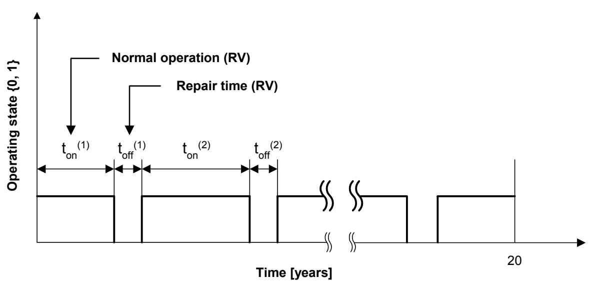

Fig. 2. The 20-year data set of PV system operation.

NUMERICAL EXAMPLE

As a numerical example, we use the failure characteristics (time to failure and repair time) determined using five years of field data for the 315kW single-inverter PV system installed at the Georgia Tech Aquatic Center in Atlanta, GA [3]. We assume that both variables are Weibull distributed, with corresponding scale (η) and shape (β) parameters estimated from the field data. The Monte Carlo analysis is performed for all three inverter configurations already mentioned: string inverters, parallel inverters and parallel inverters with selective inverter shutdown in order to maintain highest conversion efficiency possible. The corresponding MTBF and mean time to repair (MTTR) are 540 days and 26 days respectively.

The DC output of the reference single-inverter PV system at a given location is simulated using the PV simulation program (PVGRID 7.1 in our example), with weather input derived from the TMY2 database that serves as a standard database for weather conditions in the US. The inverter size for the single-inverter case is determined using the condition that the single-inverter system has to be able to process all available DC power for 99.5% of the time, i.e. only for 0.5% of the time would its power had to be limited to its nominal value. The size of each inverter in the *N*-inverter system is appropriately *N* times lower. This approach allows the comparison of results for different geographical locations, as the energy output of the PV array of the same size will be different for different locations, and an inverter of different size may be needed.

The results are summarized in Fig. 3.

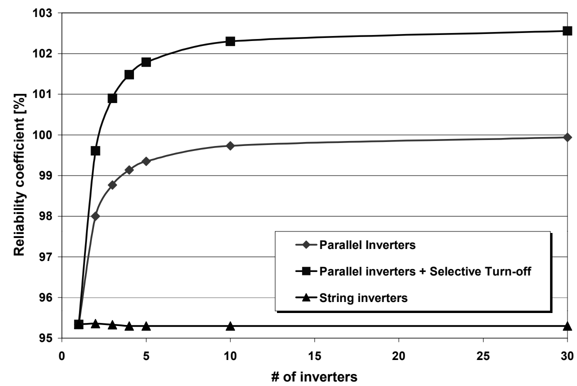

Fig. 3. The performance-adjusting reliability coefficient as a function of number of inverters in the system (using data from the GTAC PV system in Atlanta, GA).

In the case of string inverters, the expected total energy production does not depend on the number of inverters in the system. If inverters are connected in parallel, sharing the total load, the expected energy production increases as the number of inverters in the system increase. The sharpest increase is for a two-inverter system, where the total expected energy production increases by more than 2.5%, compared to the single-inverter system. As the number of inverters increases, the law of diminishing returns kicks in, and additional improvements eventually become negligible. The same behavior is experienced in the third case, when only the minimum number of inverters is operational at any given time in order to maximize the conversion efficiency. This strategy yields few more percent in energy gain, depending on the number of inverters in the system. It is interesting to note that (in this example) for systems with three or more inverters, using this control strategy, the expected lifetime energy production is actually higher than the production of the single-inverter system that has not experienced a single failure throughout its service life.

To demonstrate the effect of distribution parameters, Monte Carlo procedure was repeated for several combinations of distribution parameters for both TBF and repair time, effectively varying MTBF from 1 to 3 years and MTTR from 30 to 60 days. In all cases, the changes in MTBF and MTTR are obtained by changing only the appropriate scale (η) parameter, while keeping the shape (β) parameter constant. The results are shown in Fig. 4. As expected, increasing MTBF increases reliability coefficient, while increasing MTTR decreases it. These results are site specific; however, the general shapes of the curves are similar for several locations considered so far (Atlanta, GA, Chicago, IL and Scottsbluff, AZ). Our continuing efforts are geared towards generating a set of coefficient values that could be used for locations throughout the United States.

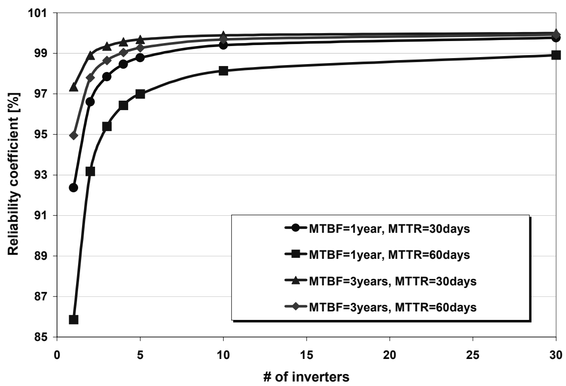

Fig. 4. The dependence of the reliability coefficient on the failure characteristics of the inverter and repair time.

OPTIMAL NUMBER OF INVERTERS: COST VS. RELIABILITY

The simulations provide a quantitatively demonstration that multiple-inverter configuration may improve system reliability, and reduce production losses due to inverter failures. However, multiple inverter configurations may have substantially higher up-front and maintenance costs that may offset any possible energy gains. We propose a relatively straightforward procedure to determine the optimal number of inverters in a PV system that minimizes the life-cycle costs of such system.

Lifetime revenues from energy production of the PV system (20 years) can be estimated using the following formula:

$$E(x) = K(x) \cdot E_1 \cdot c \cdot r \cdot \frac{1 - r^{20}}{1 - r} \tag{2}$$

where x is the number of inverters in the system, $K(x)$ is the reliability coefficient that accounts for inverter failure related downtimes, E_1 is the total annual energy production at a given location for a failure-free single inverter system in kWh, c is the energy cost in \$/kWh, and r is the coefficient that accounts for annual variations in energy price and inflation.

Multi-inverter systems usually have higher up-front and maintenance costs. The inverter price P is usually quoted in \$/VA, thus the installation and maintenance costs of the multi inverter system can be determined using:

$$C(x) = S \cdot P\left(\frac{S}{x}\right) \cdot (1 + m) \tag{3}$$

where S is the total installed inverter power, in VA, $P(y)$ is the inverter price as a function of its size, expressed in \$/VA, and m is the coefficient that accounts for the maintenance costs. Based on data from [2], we have used the following formula for the inverter price (per VA):

$$P(y) = -0.1569 \cdot \log(y) + 1.2675 \tag{4}$$

The total lifetime gain from the system, $T(x)$, expressed in \$, is simply obtained as a difference between revenues $E(x)$ and costs $C(x)$. It is a function of only the number of inverters x, which can be used to obtain the optimal number of inverters that maximizes the benefits over the lifetime of the system. Note that $T(x)$ does not include the costs associated with PV array, which are assumed to be the same in all configurations. Fig. 5. shows values for $T(x)$ as a function of the number of inverters in the system – highest value for $T(x)$ indicating optimal configuration. The parameters used for this analysis were MTBF=1 year, MTTR=30 days, c=0.12 \$/kWh, r=1.03 and m=0.15. In the example considered, a three-inverter system would yield the lowest life-cycle costs.

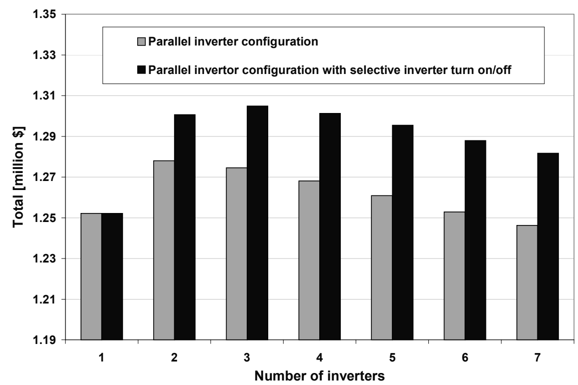

Fig. 5. The optimal number of inverters in the system.

CONCLUSIONS

The importance of including failure related downtime in PV system life cycle cost predictions is demonstrated. A new performance-adjusting coefficient that accounts for system downtimes is proposed, and a straightforward analysis for determining the optimal inverter configuration is described. Our continuing work will focus on incorporation of this procedure in a general PV simulation program, and investigating the possibility of using other inverter configurations, such as the multilevel inverters.

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